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"Tracing chromospheric evaporation in radio and soft X-rays"

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Three publications in refereed journals and several presentations at scientific conferences resulted from this work, supported by NASA grant NAGW-4581 over a period of 6 months during 1995/1996. In the first paper, the discovery of the chromospheric evaporation process at radio wavelengths is described. In the second paper, the radio detection is used to quantify electron densities in the upflowing heated plasma in flare loops, which is then compared with independent other density measurements from soft X-rays, or the plasma frequency of electron beams originating in the acceleration region. In the third paper, the diagnostic results of the chromospheric evaporation process are embedded into a broader picture of a standard flare scenario. Abstracts of these three papers are attached.

References:

1) Aschwanden,M.J. and Benz,A.O. 1995, "Chromospheric Evaporation and Decimetric Radio Emission in Solar Flares", *Astrophys. J.*, **438**, 997-1012.

2) Aschwanden,M.J. and Benz,A.O. 1997, "Electron Densities in Solar Flare Loops, Chromospheric Evaporation Upflows, and Acceleration Sites", *Astrophys. J.*, **480**, 825-839

3) Aschwanden,M.J. and Treumann,R.A. 1997, "Coronal and Interplanetary Particle Beams", (ed. G.Trottet), Lecture Notes in Physics **483**, 108-134 (Berlin:Springer)

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CHROMOSPHERIC EVAPORATION AND DECIMETRIC RADIO EMISSION IN SOLAR FLARES

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ABSTRACT

We have discovered decimetric signatures of the chromospheric evaporation process. Evidence for the radio detection of chromospheric evaporation is based on the radio-inferred values of (1) the electron density, (2) the propagation speed, and (3) the timing, which are found to be in good agreement with statistical values inferred from the blueshifted Ca XIX soft X-ray line. The physical basis of our model is that free-free absorption of plasma emission is strongly modified by the steep density gradient and the large temperature increase in the upflowing flare plasma. The steplike density increase at the chromospheric evaporation front causes a local discontinuity in the plasma frequency, manifested as almost infinite drift rate in decimetric type III bursts. The large temperature increase of the upflowing plasma considerably reduces the local free-free opacity (due to the $T^{-3/2}$ dependence) and thus enhances the brightness of radio bursts emitted at the local plasma frequency near the chromospheric evaporation front, while a high-frequency cutoff is expected in the high-density regions behind the front, which can be used to infer the velocity of the upflowing plasma. From model calculations we find strong evidence that decimetric bursts with a slowly drifting high-frequency cutoff are produced by *fundamental* plasma emission, contrary to the widespread belief that decimetric bursts are preferentially emitted at the harmonic plasma level.

We analyzed 21 flare episodes from 1991–1993 for which broadband (100–3000 MHz) radio dynamic spectra from Phoenix, hard X-ray data from BATSE/*CGRO*, and soft X-ray data from *GOES* were available. We detected slowly drifting high-frequency cutoffs between 1.1 and 3.0 GHz, with drift rates of -41 ± 32 MHz s^{-1}, extending over time intervals of 24 ± 23 s. Developing a density model for type III–emitting flare loops based on the statistically observed drift rate of type III bursts by Alvarez & Haddock (1973), we infer velocities of up to 360 km s^{-1} for the upflowing plasma, with an average of $v_{CE} = 236 \pm 130$ km s^{-1} for episodes with 5–15 s duration. The mean electron density of the upflowing plasma is $n_e = 5.2(\pm 3.1) \times 10^{10}$ cm^{-3} when it is first detected in radio, at coronal altitudes of $h_0 = 9.2 \pm 2.3$ Mm.

Subject headings: Sun: chromosphere — Sun: flares — Sun: radio radiation

1. INTRODUCTION

In the early phase of a solar flare, the plasma in a flare loop displays dynamic processes such as turbulent motion (with velocities exceeding 100 km s^{-1}) and high-speed plasma upflows (with bulk velocities of 300–400 km s^{-1}), as inferred from the line broadening and blueshift of soft X-ray (SXR) lines in Ca XIX and Fe XXV (Antonucci et al. 1982; Antonucci, Gabriel, & Dennis 1984). The upward motion of the flare plasma in the early impulsive phase is generally referred to as "chromospheric evaporation" (Sturrock 1973) and is believed to be a consequence of local heating of the chromosphere near the footpoints of flare loops, produced either by collisions from precipitating electrons (Canfield et al. 1980) or by heat conduction (Antiochos & Sturrock 1978). Chromospheric evaporation is considered to be the main mechanism for transporting the hot SXR-emitting flare plasma to coronal levels (Antonucci et al. 1984). Reviews on this subject can be found in Doschek et al. (1986), Antonucci (1989), Doschek (1990), and Antonucci et al. (1994).

The chromospheric evaporation process has thus far been studied chiefly in SXRs and Hα. In this paper we address for the first time observational evidence at radio wavelengths. The basic idea is that the local disturbance of the electron density and temperature, introduced by the upflowing chromospheric plasma, is detectable from radio bursts emitted at the local plasma frequency. Plasma emission produced by electron beams has been observed in the lower corona up to a frequency of 8.4 GHz (Benz et al. 1992). The detection of plasma emission at such high frequencies requires overdense flux tubes, so that plasma emission can escape in a direction perpendicular to the flux-tube axis, where the density scale height is much shorter than in a homogeneous corona, and thus, free-free absorption is substantially reduced. In the event of chromospheric evaporation, we expect that the upflowing plasma surrounds overdense flux tubes and seals off escape routes for plasma emission, because the additional plasma material, if sufficiently dense, makes the escape routes optically thick owing to free-free absorption. Since the evaporating plasma propagates upward with a bulk speed of ≈300 km s^{-1}, it is expected to produce a slowly drifting high-frequency cutoff for plasma emission. This high-frequency cutoff is thought to apply to any kind of plasma emission originating in "evaporating" flare loops, e.g., to type III bursts excited by precipitating electron beams. The drift rate of this high-frequency cutoff for plasma

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ELECTRON DENSITIES IN SOLAR FLARE LOOPS, CHROMOSPHERIC EVAPORATION UPFLOWS, AND ACCELERATION SITES

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ABSTRACT

We compare electron densities measured at three different locations in solar flares: (1) in soft X-ray (SXR) loops, determined from SXR emission measures and loop diameters from *Yohkoh* Soft X-Ray Telescope maps [$n_e^{\mathrm{SXR}} = (0.2\text{–}2.5) \times 10^{11}$ cm^{-3}]; (2) in chromospheric evaporation upflows, inferred from plasma frequency cutoffs of decimetric radio bursts detected with the 0.1–3 GHz spectrometer Phoenix of ETH Zürich [$n_e^{\mathrm{upflow}} = (0.3\text{–}11) \times 10^{10}$ cm^{-3}]; and (3) in acceleration sites, inferred from the plasma frequency at the separatrix between upward-accelerated (type III bursts) and downward-accelerated (reverse-drift bursts) electron beams [$n_e^{\mathrm{acc}} = (0.6\text{–}10) \times 10^9$ cm^{-3}].

The comparison of these density measurements, obtained from 44 flare episodes (during 14 different flares), demonstrates the compatibility of flare plasma density diagnostics with SXR and radio methods. The density in the upflowing plasma is found to be somewhat lower than in the filled loops, having ratios in a range $n_e^{\mathrm{upflow}}/n_e^{\mathrm{SXR}} = 0.02\text{–}1.3$, and a factor of 3.6 higher behind the upflow front. The acceleration sites are found to have a much lower density than the SXR-bright flare loops, i.e., $n_e^{\mathrm{acc}}/n_e^{\mathrm{SXR}} = 0.005\text{–}0.13$, and thus must be physically displaced from the SXR-bright flare loops. The scaling law between electron time-of-flight distances l' and loop half-lengths s, i.e., $l'/s = 1.4 \pm 0.3$, recently established by Aschwanden et al. suggests that the centroid of the acceleration region is located above the SXR-bright flare loop, as envisioned in cusp geometries (e.g., in magnetic reconnection models).

Subject headings: acceleration of particles — radiation mechanisms: nonthermal — Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

The electron density is one of the fundamental physical parameters characterizing plasma in the solar corona. The plasma of the quiet corona is supposed to be close to thermal equilibrium, and its density thus decreases exponentially with height, at least along open magnetic field lines. Electron beams that propagate through the corona can excite plasma emission, whose frequency is mainly a function of the local electron density and, thus, conveniently traces the density structure along the trajectory. However, deviations from a hydrostatic corona are common, mainly in closed magnetic structures. Heating processes in coronal loops may occur faster than the thermalization time and thus can lead to density scale heights that do not correspond to a thermal equilibrium, and vary with height. During the impulsive phase of flares especially, there is a large departure from equilibrium, with the energizing of the flare plasma resulting in a raising of the electron density as well as temperature. Moreover, chromospheric evaporation is thought to drive an upflow of heated plasma into flare loops, producing steep density gradients at the upflow front. A density diagnostic therefore represents a key tool to probe the various physical processes that evolve during solar flares.

Electron densities in flares can be measured with different methods, employing (1) the plasma frequency of coherent radio emission, (2) the emission measure of soft X-ray (SXR) or X-ray/ultraviolet (XUV) emission, (3) density-sensitive line ratios (in SXRs and the XUV; see, e.g., the review by Doschek 1990; Phillips 1991), (4) line width measurements of the higher Balmer lines (e.g., Foukal, Miller, & Gilliam 1983), or (5) measurement of the intensity of the electron scattering (white light) continuum for limb flares (e.g., Fisher 1974; Ichimoto et al. 1992). For an extensive review of electron density measurements in flare loops, see Bray et al. (1991, pp. 229–249). In this study we make use of the first two methods in radio and SXR wavelengths, by analyzing radio data from the Phoenix spectrometer (ETH Zürich) and the Soft X-Ray Telescope (SXT) on board the *Yohkoh* spacecraft. The new aspect of this investigation is to compare the electron densities inferred from decimetric radio bursts with those obtained from SXR emission measure maps of flare loops. This intercomparison should lead us to a conclusion whether electron beams that produce decimetric plasma emission propagate inside SXR-bright flare loops or outside, in a volume with lower density. Since the electron density of the acceleration site can be measured from broadband radio spectra that show bidirectional electron beams (accelerated in upward and downward directions), the comparison of its electron density with that of the SXR-bright flare loop should also reveal whether the acceleration site is located inside or outside the SXR flare loop. These observational constraints may have incisive implications for flare models, e.g., whether particle acceleration takes place in DC electric fields inside flare loops versus magnetic reconnection above flare loops. A further spin-off of this study is to probe the electron density in plasma upflows produced by chromospheric evapo-

Coronal and Interplanetary Particle Beams*

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Abstract. In this report we attempt to synthesize the results of a series of working group discussions focused on the topics of particle beams and particle acceleration in the solar corona and in interplanetary space. We start our discussion of coronal beams with a standard flare scenario, established on recent X-ray (*Yohkoh*, *CGRO*) and radio observations, which constitutes a framework for the understanding of upward and downward accelerated electron beams and their secondary signatures, such as chromospheric evaporation. The second part is dedicated to interplanetary electron and ion beams, with emphasis on their relation to coronal beams, using recent spacecraft data from *Ulysses* and *Wind*. Interplanetary electron beams can often be traced back to coronal type III sources, while there is no such relation for interplanetary ion beams. In the third part, we briefly review acceleration mechanisms for coronal and interplanetary beams, separately for electrons and ions.

Résumé. Nous résumons ici une série de discussions de groupe dont le sujet était les faisceaux de particules et l'accélération de particules dans la couronne solaire et le milieu interplanétaire. Nous débutons notre discussion par les faisceaux coronaux dans le cadre d'un modèle standard d'éruption solaire, établi à la suite d'observations récentes dans le domaine des rayons X (*Yohkoh*, *CGRO*) et le domaine radioélectrique. Ce modèle standard est le cadre de travail nécessaire à une meilleure compréhension de la propagation des faisceaux d'électrons accélérés, ainsi que de leurs effets secondaires, comme l'évaporation chromosphérique. La seconde partie de notre synthèse traite des électrons et faisceaux d'ions dans le milieu interplanétaire, et en particulier de leur relation avec les faisceaux coronaux, grâce à l'utilisation de données récentes obtenues par les missions *Ulysses* et *Wind*. Si les faisceaux d'électrons interplanétaires sont souvent associés à des faisceaux coronaux émetteurs de sursauts de type III, ce n'est pas le cas pour les faisceaux d'ions interplanétaires. Dans la troisième partie nous résumons brièvement les mécanismes d'accélération des faisceaux coronaux et interplanétaires, en discutant séparément l'accélération des électrons et des ions.

1 Introduction

This report originated from a series of presentations and discussions about the role of particle beams (electrons, ions) as a cause of various emissions (radio,

* Working Group Report

[1] Lecture Notes in Physics **483**, p.108-131, Conf. Proc. of *Community of European Solar Radio Astronomers (CESRA)* Workshop on *"Coronal Physics from Radio and Space Observations"*, held in Nouan le Fuzilier, France, 1996, June 3-7, (eds. G.Trottet), Berlin:Springer.